Towards Identifying Contribution of Wake Turbulence on Inflow Turbulence Noise from Wind Turbines

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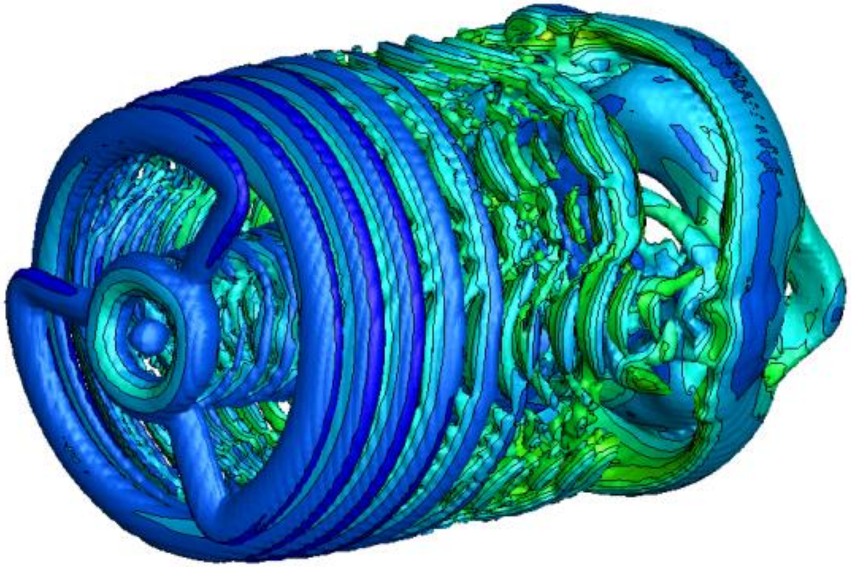

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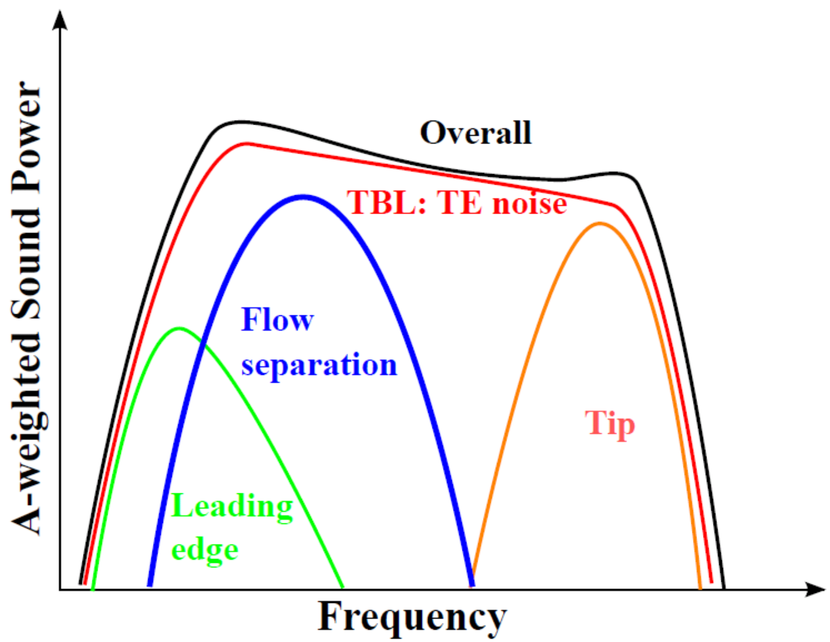
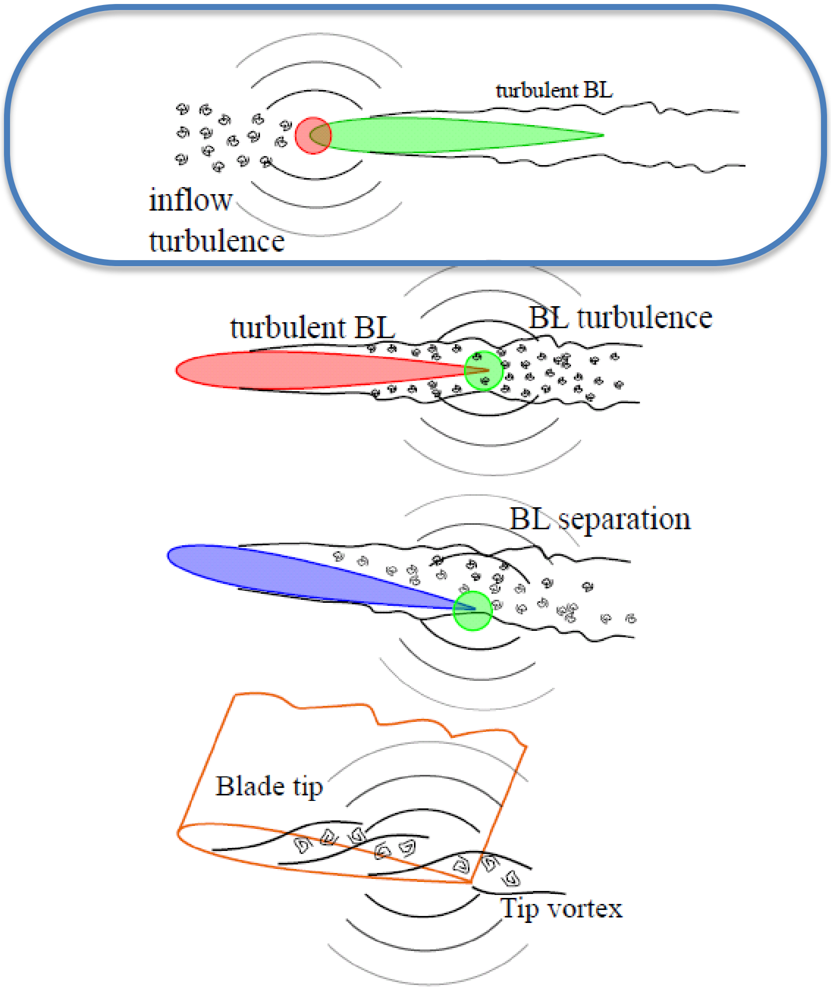
HAWT: Aerodynamic Noise Sources

- Various aero noise sources:
  - Turbulence interaction with blades
  - Unsteady force → noise
- Focus on inflow turbulence here
  - Important for low-frequency noise





Motivation

- Lighthill's acoustic analogy – unsteady force → noise source

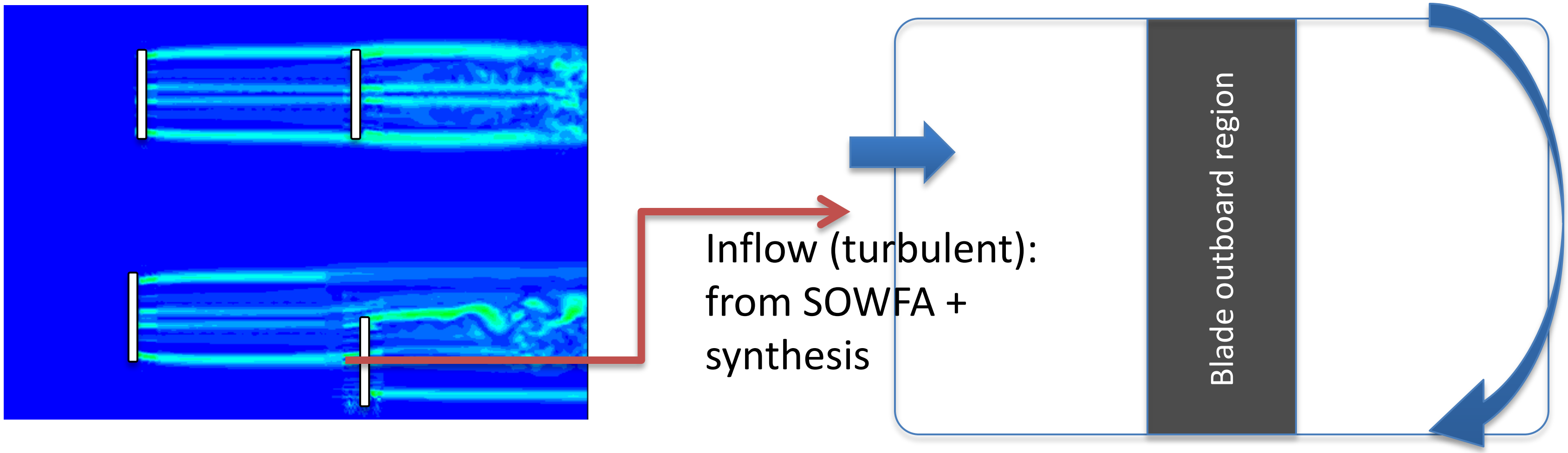
$$\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \frac{\partial^2 \rho'}{\partial {x_i}^2} = \frac{\partial m}{\partial t} - \boxed{\frac{\partial f_i}{\partial x_i}} + \frac{\partial^2}{\partial x_i \, \partial x_j} \underbrace{\left(p_{ij} + \rho u_i u_j - \rho' c_0^2 \delta_{ij}\right)}_{T_{ij}},$$

- Sources of inflow turbulence
  - **Atmospheric:** buoyancy & shear
  - Turbine wakes: shear

- Role of wake turbulence in producing noise is unclear
  - possibly pronounced under *stable* conditions
  - potential for OAM (other amplitude modulation)

Envisioned Prediction Approach

Aero: LES (SOWFA) **Acoustics:** LES (pisoFoam)



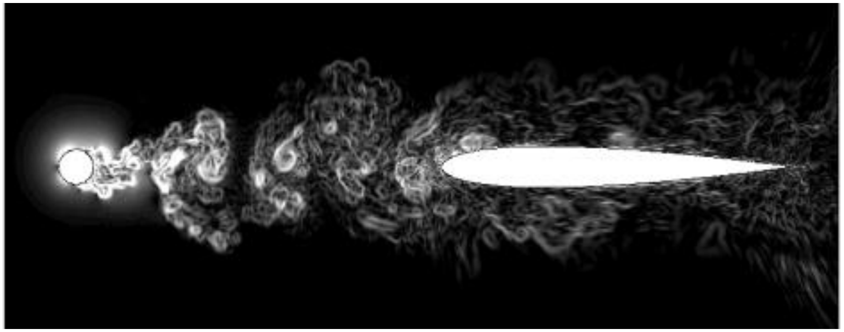
- SOWFA calculations
  - Sample wake (+atmospheric) turbulence statistics
  - Prescribe as inflow BC to aeroacoustic simulation

- Simulate outboard section of turbine blade
  - Ignore rotational effects, assume periodicity in span
  - Prescribe inflow turbulence (synthesized?)
  - LES + model → noise resulting from inflow turbulence-blade interaction

Simplified (model) Problems *for now*

- **I:** Farm Aero
  - SOWFA calculations … no ABL
  - Time history probes at hub height
    → Turbulence length scale + intensity
  - Lowson/Amiet noise model → far-field noise

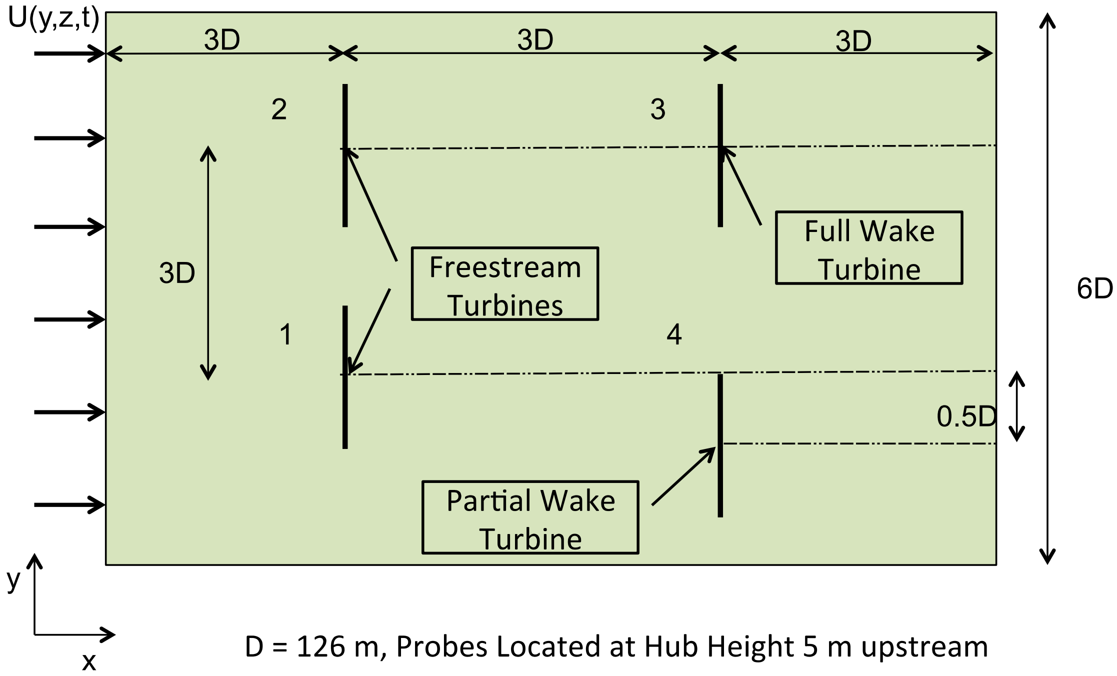
- **II:** Rod-Airfoil interaction
  - Rod wake simulates upstream wake turbulence
  - Compute airfoil response (loads/noise) using LES
  - Acoustics analogies → far-field noise



I: FARM AERO (SOWFA)

Hypothetical Wind Farm

- Wind farm layout
  - Turbines under: no-wake, partial-wake, & full-wake



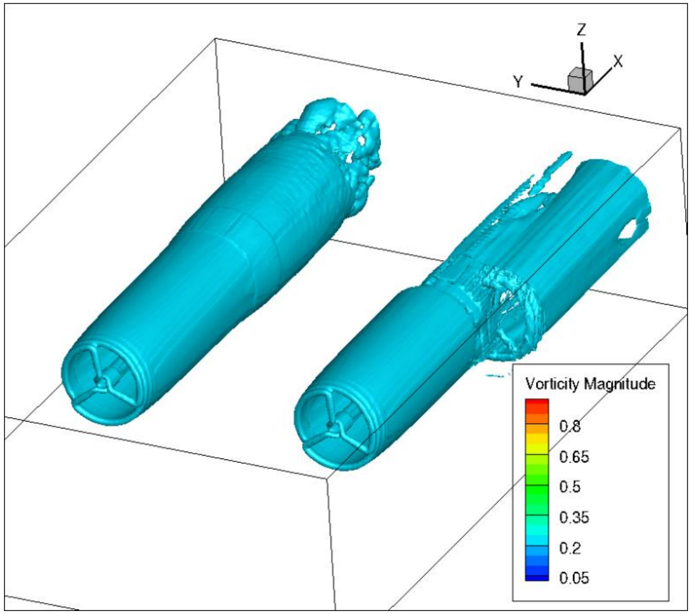
D = 126 m, Probes Located at Hub Height 5 m upstream

- Aero calculations using SOWFA
- Wake turbulence data extracted at hub height

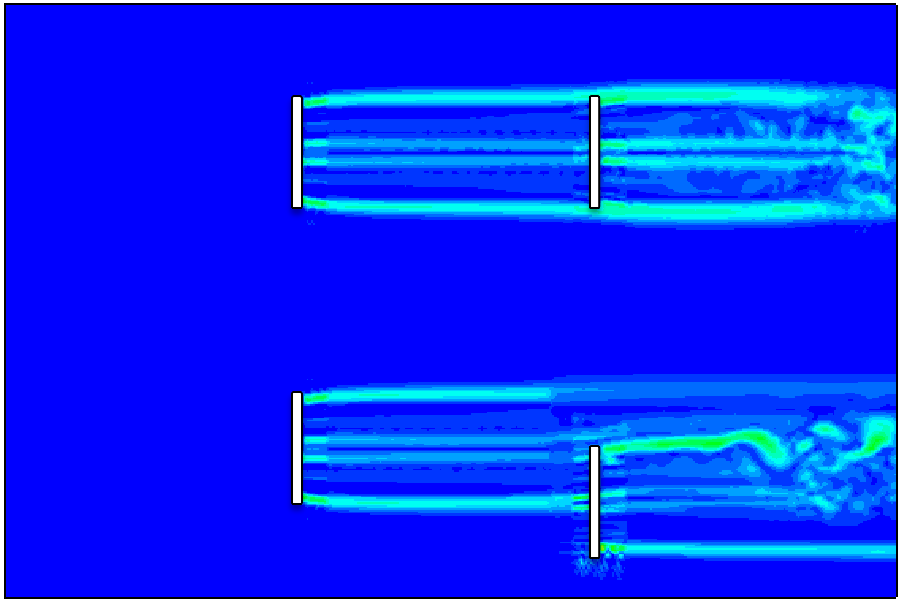
Aerodynamic Results

- SOWFA: pisoFoam + actuator line model
- At the moment: No ABL → first row of turbines have no inflow turbulence

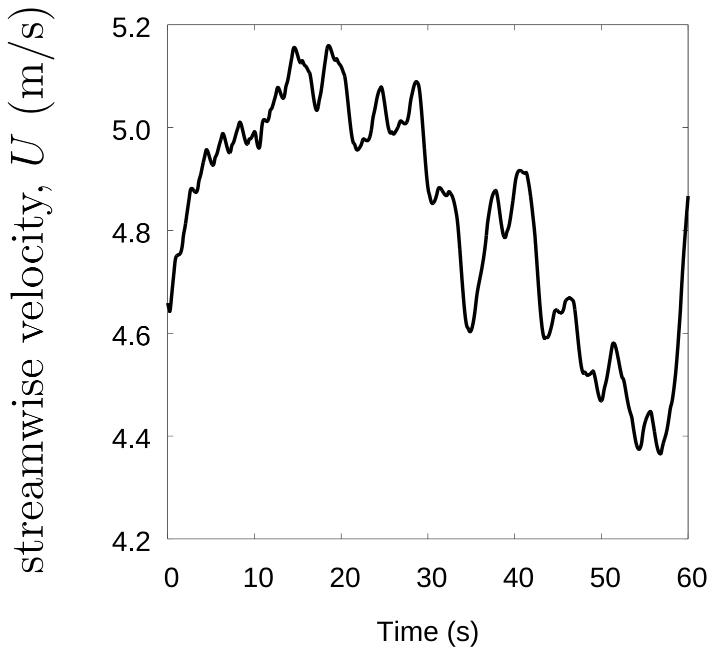
Iso-vorticity surfaces

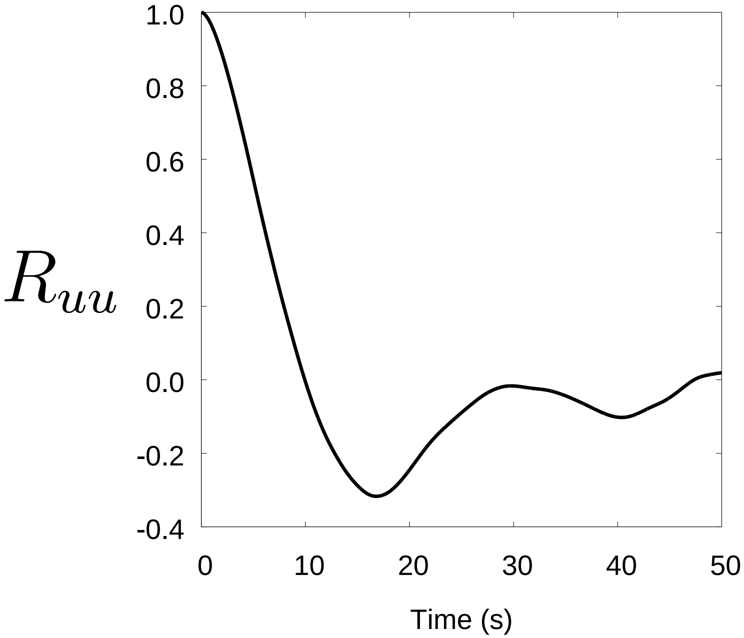


Vorticity magnitude contours



Wake Turbulence Information





- Time history (streamwise velocity component)
- Auto-correlation: $R_{uu}(\tau) = \dfrac{\langle u(t)u(t+\tau)\rangle}{\langle u^2(t)\rangle}$; where $u = U - \langle U \rangle$
- Integral time scale: $T = \int_0^\infty R_{uu}(\tau)\,\mathrm{d}\tau$
- Integral length scale … use Taylor's frozen turbulence hypothesis: $l_t = \bar{U} \times T$

Inflow Turbulence Noise Model

- Due to Lowson … extension of Amiet's theory

$$\mathrm{SPL}^H_{1/3} = 10\log_{10}\left[(\rho_0 c_0)^2 \frac{L}{2\,r_o^2} l_t M^3 I^2 U^2 \frac{K^3}{(1+K^2)^{-7/3}}\right] + 58.4$$

$$\begin{aligned} l_t &\rightarrow \text{integral length} \\ I &\rightarrow \text{turbulence intensity} \\ U &\rightarrow \text{flow speed} \\ L &\rightarrow \text{airfoil span} \\ K &= \omega c/(2U_{rel}) \rightarrow \text{wavenumber based on semichord } c/2 \end{aligned}$$

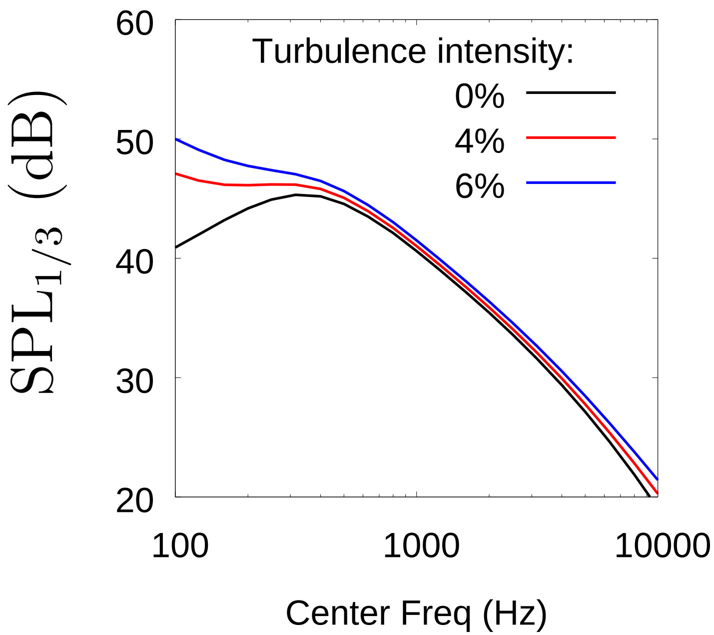
- Correction for low frequencies

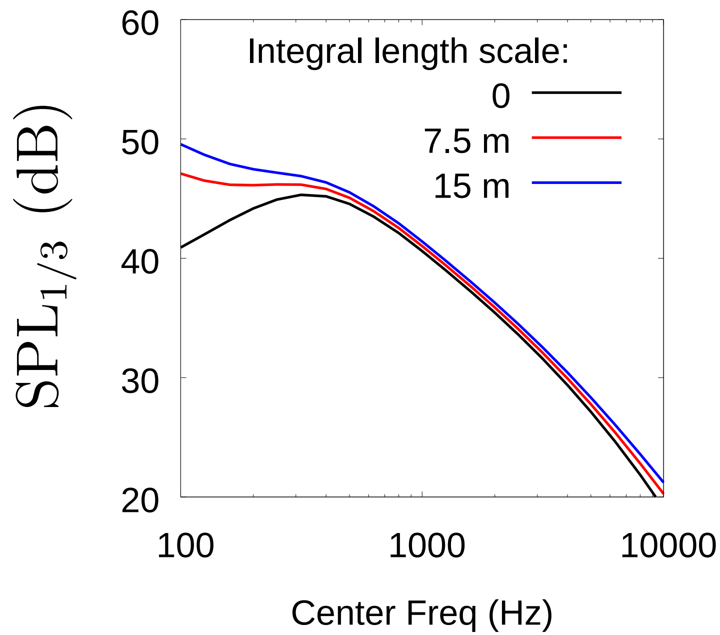
$$SPL^L{}_{1/3} = SPL^H{}_{1/3} + 10\log_{10}\left(\underbrace{10\,S^2\,MK^2/(1-M^2)}_{\text{low freq corr}}\right)$$

… S^2 is the compressible Sears function

Noise Results (preliminary)

- Wake turbulence: TI ~ 5-10%; length scale ~ 2-10 m
- Lowson's model (in FAST) used to assess noise at IEC std. observer location
- Noise predictions for a few representative values of TI & length scales



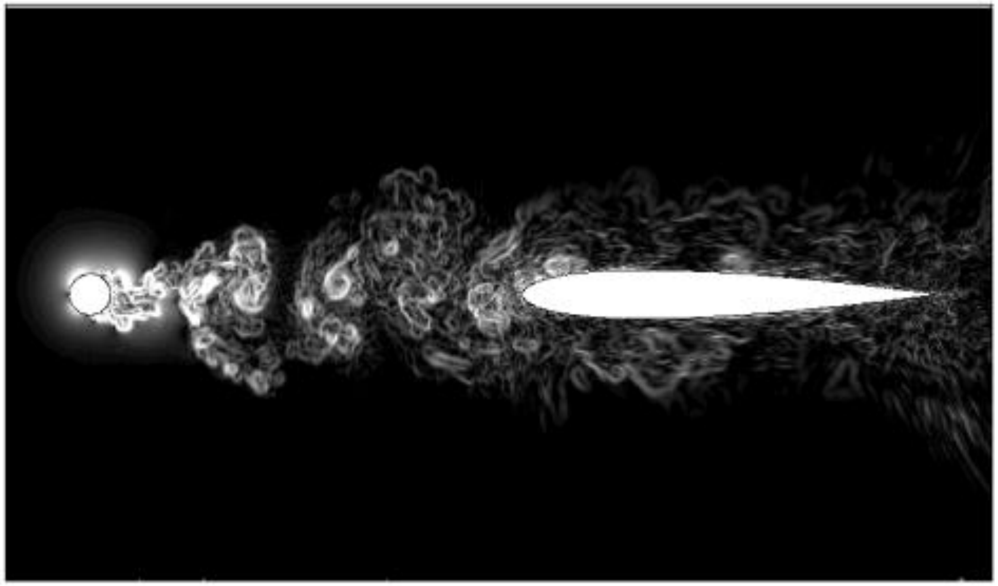


- Perceptible impact on low-frequency noise
- However, the question of relative importance of wake/atmospheric turbulence remains

II: ROD-AIRFOIL

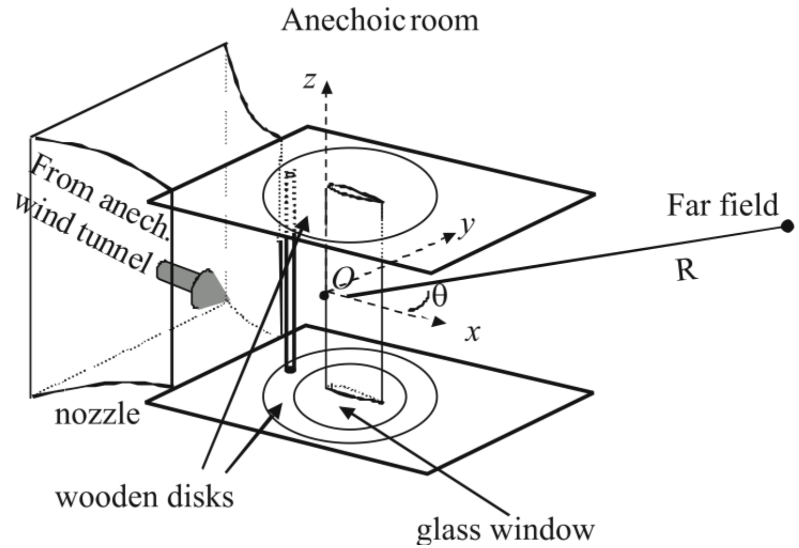
Model Problem: Rod-Airfoil

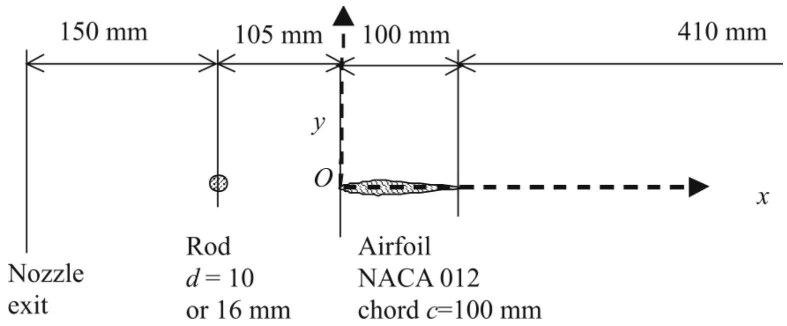
- Rod → turbulence generator (mimic inflow turbulence)
- Wake-airfoil interaction → noise
- Rod wake comprises of:
  - Quasi-periodic vortex shedding → tone noise
  - Vortex structure breakdown → turbulence → broadband noise



Rod Airfoil Problem Setup

- Experiment by Jacob *et al.* [1]
- Setup:
  - Rod airfoil in tandem
  - Airfoil (NACA 0012; c = 0. 1 m)
  - Rod (dia, d = 0.01 m)
  - Separation, l = 0.1 m
- Flow Reynolds number:
  - Re_d = 48,000 (Re_c=480,000)
- Rod (cylinder) vortex shedding
  - Wake shedding St = 0.19



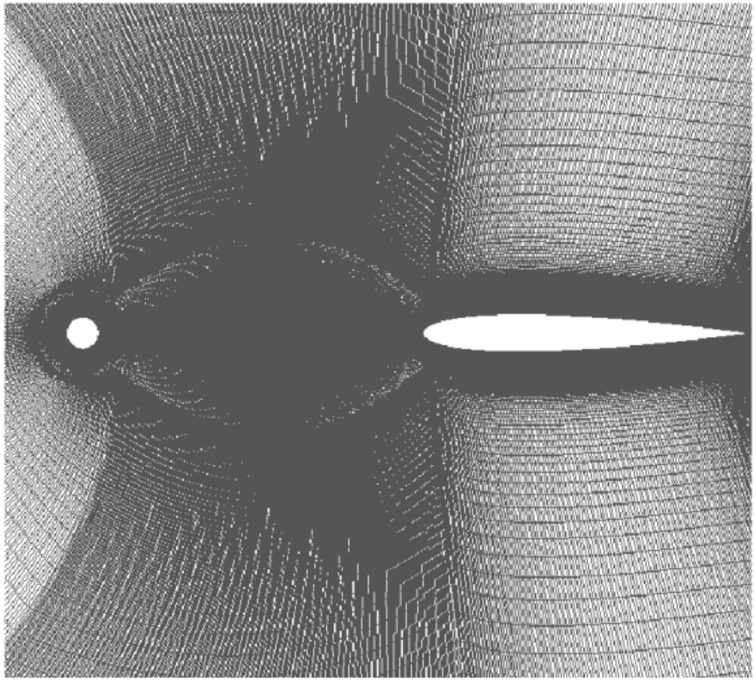


1. Jacob, M. C., Boudet, J., Casalino, D., and Michard, M., "A rod-airfoil experiment as a benchmark for broadband noise modeling," *Theoretical and Computational Fluid Dynamics*, Vol. 19, 2005, pp. 171-196.

Large Eddy Simulations

- Two flow solvers benchmarked against experiments
  - Compressible flow solver **Charles** by Cascade Tech.
  - Incompressible flow solver **pisoFoam** from OpenFoam

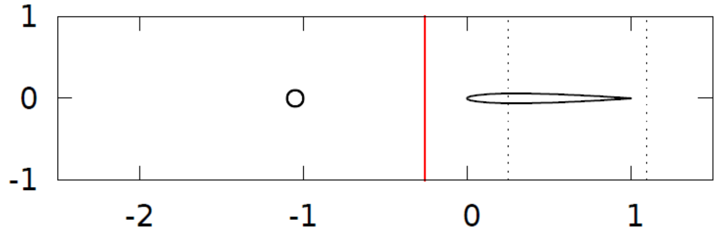
- Grid refined to resolve
  - Rod & airfoil boundary layers
  - Gap region between rod and airfoil



- Flow initialized by interpolating a 2-D solution

Flow Comparisons

- Streamwise velocity in wake
  - at *x/c* = -0.255
  - Mean and fluctuation (rms)



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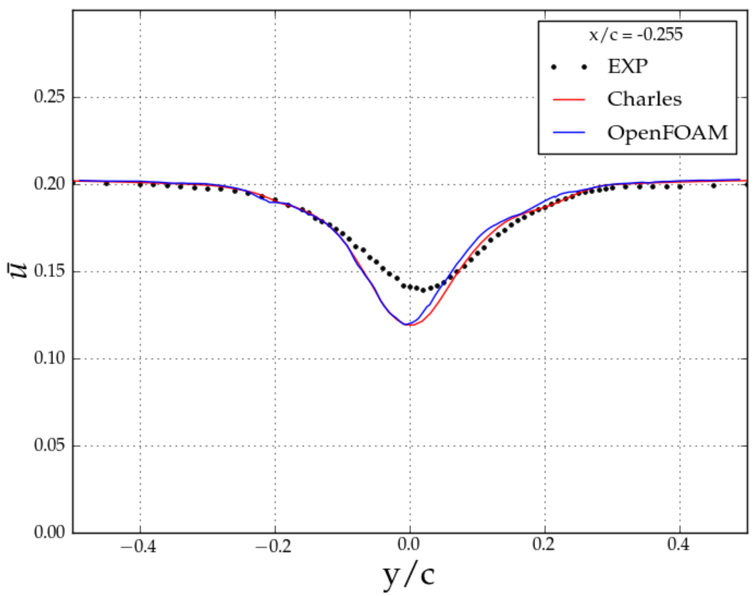
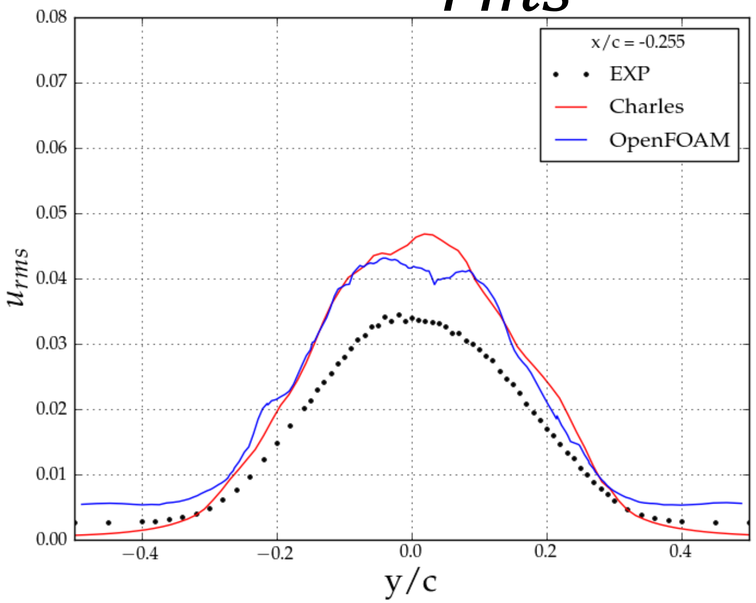
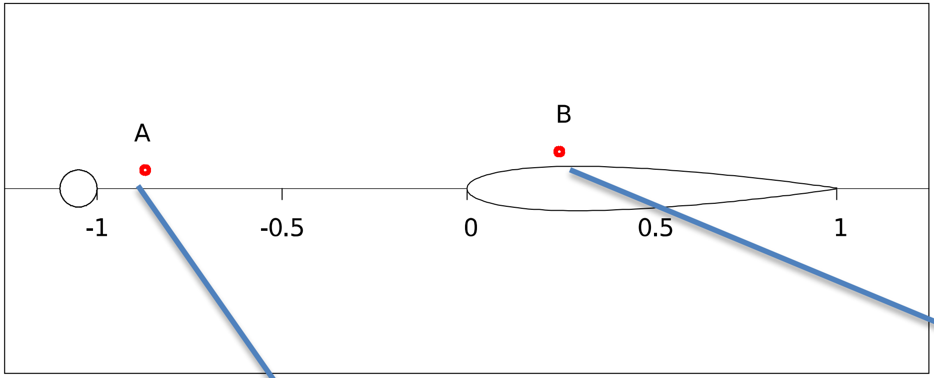


u_{rms}

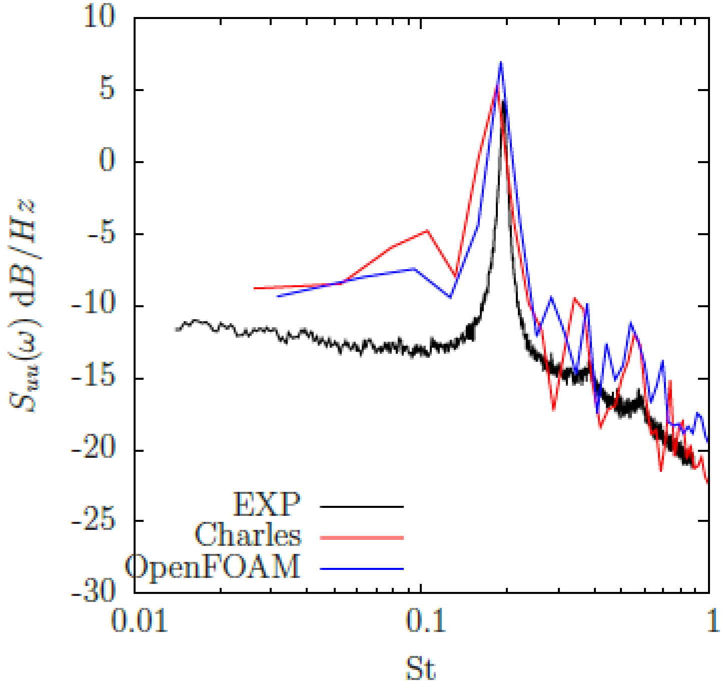


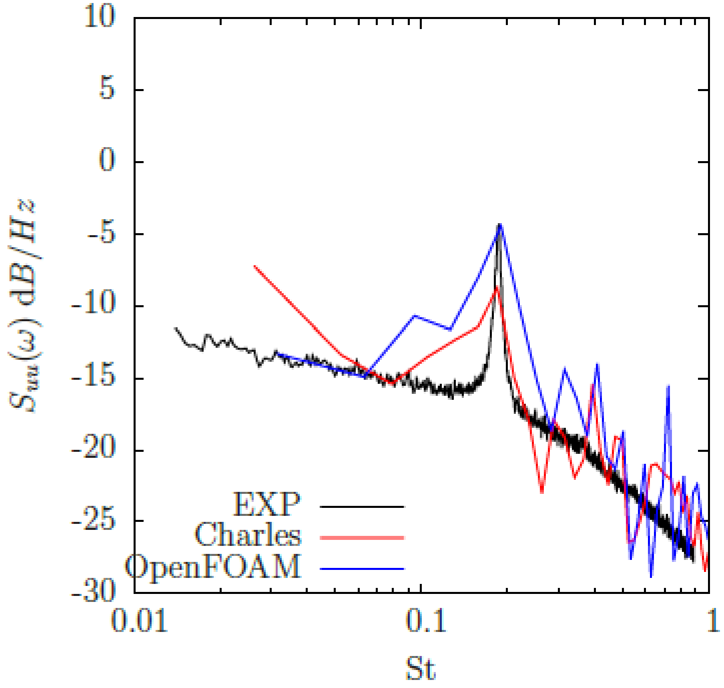
Near Field Velocity Spectral Density, $S_{uu}(\omega)$



PSD: using Wiener-Khinchin theorem:

$$S_{uu}(\omega) = \frac{\delta t}{N} \left| \sum_{n=1}^{N} u_n \exp(-i\omega\, n\delta t) \right|^2$$





Far-field Noise Prediction

Acoustic analogies to predict far-field noise

- Compressible flow data:
  - Ffowcs Williams-Hawkings analogy (ignore volume integral)

$$
\begin{aligned}
4\pi|\mathbf{x}|p'(\mathbf{x},t) &= \frac{x_i}{c|\mathbf{x}|}\frac{\partial}{\partial t}\int \left[p'n_i + \rho u_i(u_j - U_j)n_j\right] \, \mathrm{d}\Sigma \\
&+ \frac{\partial}{\partial t}\int \left[\rho_0 u_i + \rho'(u_i - U_i)\right] n_i \, \mathrm{d}\Sigma.
\end{aligned}
$$

- Incompressible flow data *(no density perturbation)*:
  - Amiet's theory
  - Lighthill stress tensor + scattering problem
    - Euler equations, Boundary value, etc.

Amiet's Theory

- Subtract surface pressure: pressure – suction sides to calculate loading → Delta P

- Compute cross PSD of loading on airfoil camber surface

$$S_{QQ}(x_1, x_2, y_1, y_2, \omega) = \lim_{T \to \infty} \left\{ \frac{\pi}{T} E\left[\Delta\hat{P}_T^*(x_1, y_1, \omega) \Delta\hat{P}_T(x_2, y_2, \omega) \right] \right\}$$

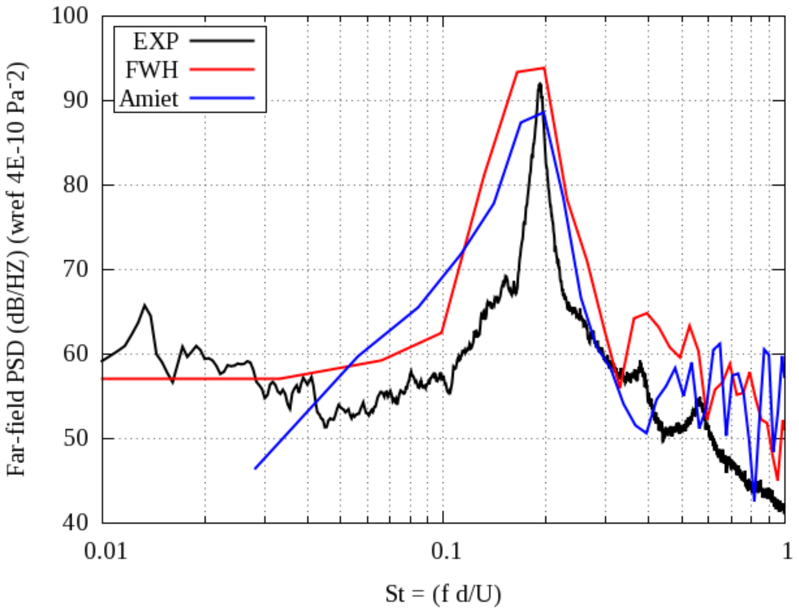
- Convolve cross PSD with free-space Green's function (of convected wave eq.) to get far-field PSD

$$\begin{aligned} S_{PP}(x, y, z, \omega) \quad &= \quad \left(\frac{\omega z}{4\pi c_0 \sigma^2} \right)^2 \\ &\iiiint S_{QQ}(x_1, x_2, \eta, \omega) \exp\left\{ \frac{i\omega}{c_0} \left[\frac{(x_1 - x_2)(M - x/\sigma)}{\beta^{-2}} + \frac{y\eta}{\sigma} \right] \right\} \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}y_1 \, \mathrm{d}y_2 \end{aligned}$$

Far Field Noise Power Spectral Density, $S_{pp}(\omega)$

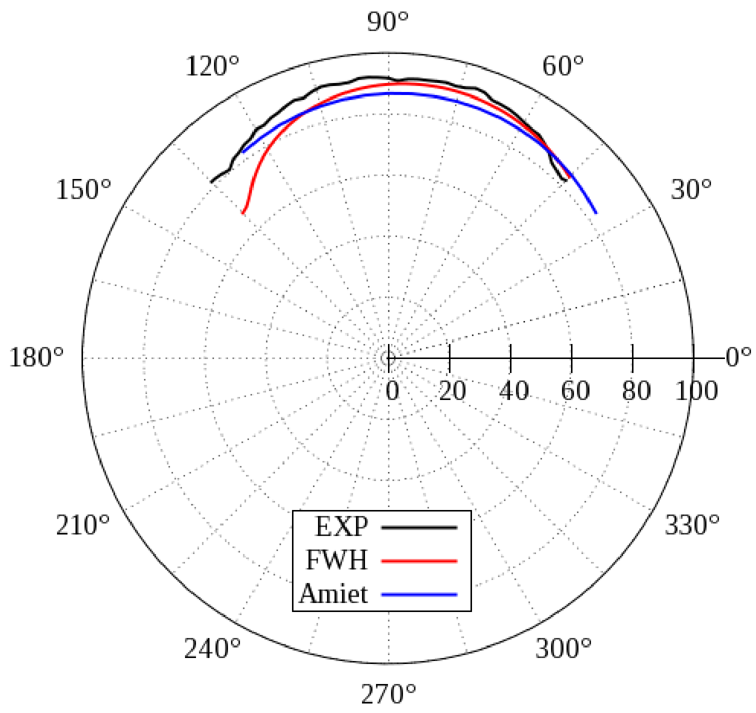
- At $18.5c$ from mid point of leading edge along lift direction
- Charles: Ffowcs-Williams Hawkings Analogy & Amiet's Formula
- Different span in Exp. and CFD (3:1)
  - For one-to-one comparison (if $L_{sim} > L_{corr}$):

$$(S_{pp}(\omega))_{sim\ \ corrected} = (S_{pp}(\omega))_{sim} + 10\log\left(\underbrace{L_{exp}/L_{sim}}_{3}\right)$$



Far Field Noise – Peak Directivity

- Noise measurement data available on a circular arc ($r = 18.5\ c$)
- Dipole directivity (as expected)
- Convective amplification – increased power upstream



Conclusions and Future Work

Conclusions:

- Progressing towards assessing impact of wake turbulence on turbine noise
- Model problems solved to assess prediction accuracy
- Rod-airfoil problem → reasonable accuracy in near- and far-field spectra

Future Work:

- Wind farm calculations with ABL inflow (stable conds)
- LES calculation of part-span blade with inflow turbulence from SOWFA calculations

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